IEEE Standard for Qualification of Class 1E Transformers for Nuclear Power Generating Stations

Sponsor

Transformers Committee
of the
IEEE Power Engineering Society

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IEEE Standards Board

Abstract: Procedures for demonstrating the adequacy of new Class 1E transformers, located in a mild environment of a nuclear power generating station, to perform their required safety functions under postulated service conditions are presented. Single and three phase transformers rated 601 V to 15 000 V for the highest voltage winding and up to 2500 kVA (self-cooled rating) are covered. Because of the conservative approach used in the development of this new standard for new transformers, the end point criteria cannot be used for in-service transformers.
Keywords: Class 1E transformers, design qualification, seismic qualification

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Foreword

(This foreword is not a part of IEEE Std 638-1992, IEEE Standard for Qualification of Class lE Transformers for Nuclear Power Generating Stations.)

IEEE Std 323-1983 was developed to provide guidance for demonstrating and documenting the qualification of electrical equipment used in all Class IE and interface systems.

This document (IEEE Std 638-1992) was developed to provide specific methods and test procedures for the qualification of Class lE transformers in accordance with IEEE Std 323-1983.

The qualifying tests described in this standard have been established for application to new transformers. This industry experience, together with a combination of some or all of the methods described, has the capability of demonstrating a qualified life of transformers up to 40 years or more. These criteria form the basis for documenting qualification of transformers for nuclear power generating stations.

Because of the conservative approach used in the development of this standard for new transformers, the end point criteria cannot be used for in-service transformers. Criteria representative of actual operating conditions should be used to qualify such transformers.

Additionally, the appendix discusses state-of-the-art technology pertaining to the evaluation of transformer insulation materials and systems, its applicability to the aging of transformers, and its relationship to “real time.” Transformer loading guides are also referenced that include procedures developed to calculate the relative fraction of insulation life considered to be expended under various loading conditions.

Based on loading and existing aging guidance, it can be demonstrated that use of insulation systems at a reduced temperature will result in reduced aging of the insulation system during the design life of a transformer. See A2.3 for an example.

Adherence to this document alone may not suffice for assuring public health and safety since it is the integrated performance of structures, fluid systems, instrumentation systems, and electrical systems of the nuclear power generating station that establish safe operating conditions.

This document was prepared by the Working Group on Qualification of Class lE Transformers of the Performance Characteristics Subcommittee of the IEEE Transformers Committee.

At the time that this standard was completed, the Working Group on Qualification of Class lE Transformers had the following membership:

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C. Hurty		D. S. Takach

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IEEE Standard for Qualification of Class 1E Transformers for Nuclear Power Generating Stations

1. Scope

This standard provides requirements to demonstrate the adequacy of new Class IE transformers, located in a mild environment of a nuclear power generating station as defined in IEEE Std 323-1983 [16][1], to perform their required safety functions under postulated service conditions. This standard applies to single and three phase transformers rated 601 V to 15 000 V for the highest voltage winding and up to 2500 kVA (self-cooled rating).

2. Purpose

The purpose of this standard is to provide specific qualification procedures for Class lE transformers to demonstrate their capability to meet the requirements of IEEE Std 323-1983 [16]. The transformer must perform its intended function under all specified service conditions.

3. References

[1] ANSI C57.12.70-1978 (Reaff 1987), American National Standard Terminal Markings and Connections for Distribution and Power Transformers.[2]

[2] ANSI C84.1-1989, American National Standard Voltage Ratings for Electric Power Systems and Equipment (60 Hz).

[3] IEEE C57.12.00-1987, IEEE General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers (ANSI).[3]

[1]The numbers in brackets correspond to those of the references listed in Section 3.
[2]ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.
[3]IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[4] IEEE C57.12.01-1989, IEEE General Requirements for Dry-Type Distribution and Power Transformers Including Those With Solid Cast and/or Resin-Encapsulated Windings.

[5] IEEE C57.12.56-1986, IEEE Test Procedure for Thermal Evaluation of Insulation Systems for Ventilated Dry-Type Power and Distribution Transformers (ANSI).

[6] IEEE C57.12.80-1978 (Reaff 1992), IEEE Standard Terminology for Distribution and Power Transformers (ANSI).

[7] IEEE C57.12.90-1987, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and Guide for Short-Circuit Testing of Distribution and Power Transformers (ANSI).

[8] IEEE C57.12.91-1979, IEEE Test Code for Dry-Type Distribution and Power Transformers.

[9] IEEE C57.91-1981 (Reaff 1991), IEEE Guide for Loading Mineral-Oil-Immersed Overhead and Pad-Mounted Distribution Transformers Rated 500 KVA and Less With 65 °C or 55 °C Average Winding Rise (ANSI).

[10] IEEE C57.92-1981 (Reaff 1991), IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers up to and Including 100 MVA With 55 °C or 65 °C Average Winding Rise (ANSI).

[11] IEEE C57.94-1982 (Reaff 1987), IEEE Recommended Practice for Installation, Application, Operation, and Maintenance of Dry-Type General Purpose Distribution and Power Transformers (ANSI).

[12] IEEE C57.96-1989 (Reaff 1992), IEEE Guide for Loading Dry-Type Distribution and Power Transformers (ANSI).

[13] IEEE C57.100-1986 (Reaff 1992), IEEE Standard Test Procedure for Thermal Evaluation of Oil-Immersed Distribution Transformers (ANSI).

[14] IEEE Std 98-1984 (Reaff 1992), IEEE Standard for the Preparation of Test Procedures for the Thermal Evaluation of Solid Electrical Insulating Materials (ANSI).

[15] IEEE Std 100-1988 IEEE Standard Dictionary of Electrical and Electronic Terms (ANSI).

[16] IEEE Std 323-1983 (Reaff 1990), IEEE Standard for Qualifying Class lE Equipment for Nuclear Power Generating Stations (ANSI).

[17] IEEE Std 344-1987, IEEE Recommended Practice for Seismic Qualification of Class lE Equipment for Nuclear Power Generating Stations(ANSI).

4. Definitions

The definitions used in this standard coincide with those defined in IEEE Std 100-1988 [15], IEEE Std 323-1983 [16], IEEE Std 344-1987 [17], and IEEE C57.12.80-1978 [6]. Definitions not previously defined but used in this standard are indicated below.

design family: A group of transformer designs that share common characteristics such as design arrangement, materials, and design stresses to meet performance characteristics such as temperature rise, impedance, losses, and seismic capability. Due to different ratings, the transformers may have dimensional differences.

5. Transformer Specifications

Class 1E transformer specifications shall include the following minimum information in addition to transformer rating data.

5.1 Service Conditions

In addition to the service conditions in IEEE C57.12.00-1987 [3] or IEEE C57.12.01-1989 [4], the conditions resulting from normal, abnormal, and design basis events shall be specified.

5.2 Equipment Performance Requirements

The equipment specification shall define the acceptance criteria and the safety functions required to be performed by the transformer during normal and abnormal service conditions, before, during, and after the design basis events, and the duration of the conditions.

5.3 Seismic Requirements

1) Required response spectra (RRS), including damping factor for both horizontal and vertical components of motion of an operating basis earthquake (OBE)
2) Required response spectra (RRS), including damping factor for both horizontal and vertical components of motion of a safe shutdown earthquake (SSE)

5.4 Electrical, Mechanical, and Structural Interfaces

Sufficient detail of interfaces between the transformer and connected equipment shall be specified to allow simulation of physical loads during seismic tests, as stated in 7.4. Lead support systems, connectors, conduit systems, mounting details, etc., are specific examples.

5.5 Industry Codes and Standards

The specific industry codes and standards to which the transformer is to be built, qualification tested, and routine tested shall be specified.

5.6 Impedance

The specification should include a requirement for measuring and recording the impedance value on each tap position. This information may be useful for detailed load flow studies.

5.7 Shipping, Storage, and/or Handling Requirements

Shipping, storage, and handling requirements shall be specified, including limitations and/or any special requirements.

5.8 Margin

The equipment specification shall include the required ratings and performance criteria, including any required margins within the context and intent of IEEE Std 323-1983 [16].

6. Approaches to Transformer Qualification

The following approaches are acceptable for use in transformer qualification. Transformers to be qualified shall meet all applicable requirements of the C57 series of standards (see Section 3).

6.1 Testing

Transformer tests are conducted as combinations of “routine” and “design” tests, as described in Section 7. These tests are defined in IEEE C57.12.80-1978 [6], and requirements and test procedures are described in IEEE C57.12.00-1987 [3], IEEE C57.12.01-1989 [4], IEEE C57.12.90-1987 [7], IEEE C57.12.91-1979 [8], and IEEE Std 344–1987 [17]. Successful completion of these tests is essential to qualification and to demonstrating that the transformer is capable of meeting the performance requirements in the user's specification.

6.2 Thermal Life Qualification

When thermal aging effects based on qualified life of insulation and support systems have been demonstrated to be negligible, seismic tests may be performed without prior thermal aging.

When thermal aging effects based on qualified life cannot be demonstrated to be negligible, then the following approach may be used to evaluate thermal life of the transformer. This should be performed prior to seismic testing of the referenced transformer.

Due to limitations related to physical size, energy requirements, and elapsed time, thermal aging of a complete transformer may not be practical. Also, because of the probable inability of thermal aging procedures to condition a complete transformer to a known end of qualified life, attempting to thermally age a complete transformer prior to qualification testing is not practical. Therefore, in lieu of thermally aging a complete transformer, it is acceptable to thermally age windings, components, or valid insulation system models/materials (accurately representing transformer designs to be qualified) to determine the thermal effects expected to accrue during the transformer’s operating life.

Acceptable aging procedures and end point testing are outlined in IEEE C57.12.56-1986 [5] or IEEE C57.100-1986 [13]. Other thermal aging procedures may be used provided that justification is agreed upon between supplier and purchaser.

6.3 Thermal Analysis and Calculation

Transformer loading guides IEEE C57.91-1981 [9], IEEE C57.92-1981 [10], and IEEE C57.96-1959 [12] include procedures for calculating conservative estimates of the fraction of transformer life expectancy that is expended under various temperature and/or loading conditions. Operation of a transformer at less than the rated insulation system temperature will reduce aging of the insulation system during its design life, as shown in A2.2.

6.4 Operating Experience

Operating experience documentation of 40 years or more may be available. However, detailed auditable data to support the actual transformer load profile is usually not available. To establish qualification by operating experience, consideration of the factors described below may be useful.

1) The same basic design and insulation system shall have been utilized.
2) Auditable records by expert engineers (such as those responsible for the design or the resolution of field problems) concerning the difficulties (or lack thereof) experienced with the generic design family under consideration shall be utilized.
3) Actual user's records documenting the environmental, seismic, and electrical loading conditions shall be included in the report.

6.5 Qualification by Analysis and Test

Qualification by analysis and test may be accomplished utilizing techniques such as the following:

1) When analytical modeling is used to demonstrate the performance behavior, the model shall yield calculated values that are within 10% of tested values for the same parameters. The source for component performance data should be reported. The analytical model should be available for third party review as well as the assumptions, test data, conditions, and accepted industry practices.
2) Physical, chemical, and engineering data may be utilized to predict the performance of transformers or components thereof.
3) Where appropriate, and to avoid repeating tests, data obtained from technical literature surveys may be used to demonstrate anticipated performance of materials when the source references are available to the public and when actual test data supports the literature.
4) The data used to support qualification by analysis shall be pertinent to the application and shall be available in an auditable form.

7. Design Qualification Procedure

7.1 General

Tests shall be performed on a transformer of a design family to demonstrate that the design meets or exceeds the conditions of the specification (see Section 5). The test program shall consist of a planned sequence of tests documented in a test specification or procedure, which will verify the transformer design and satisfactory operation under specified conditions. The extrapolation of these tests for all ratings of the design family shall be documented and justified.

Qualified life for a transformer of a design family may be determined using approaches to transformer qualification listed under Section 6 or loading guides listed in Section 3. Failures that occur during design or life testing shall be addressed in determining the qualified life. Any redesign of the transformer or change(s) of the organic components may require a retest and/or analysis of the redesign.

7.2 Test Unit

It is the intent of this section to require testing of a full size production line transformer that incorporates essential components and accessory equipment. The qualification tests that verify the performance required by the user’s specification are the routine and design tests. Routine tests shall be conducted on each transformer manufactured and on the prototype transformer used for design tests. Design tests (including temperature test, impulse test, and short-circuit test), as defined in appropriate ANSI and IEEE standards, plus seismic tests as defined in IEEE Std 344–1987 [17], are conducted on the prototype unit.

The transformer chosen for such tests shall be a representative unit of a design family in that it shall have the same design features and material specifications. Operating stresses and electrical/structural loads shall be no less severe than those for all transformers to be qualified. Design test reports shall identify all materials, test methods (including quality control), and features not specifically representative of the transformer being qualified, justifying differences in each parameter by analysis, operating experience, or independent testing.

7.3 Qualification Tests

The following routine and design tests shall be made on the prototype transformer in the order indicated in accordance with applicable requirements of IEEE C57.12.00-1987 [3], IEEE C57.12.01-1989 [4], IEEE C57.12.90-1987 [7], or IEEE C57.12.911979 [8], unless otherwise indicated. If other tests or test sequences are specified, justification for the order in which they are included in the sequence shall be mutually agreed upon by the user and the manufacturer and included in the qualification report.

1) Resistance measurements of all windings on the rated voltage connection and at the tap extremes
2) Ratio tests on the rated voltage connection and on all tap connections
3) Polarity and phase relation tests on the rated voltage connections
4) No-load losses and excitation current test at rated voltage and frequency on the rated voltage connection
5) Impedance and load loss test at rated current and rated frequency on the rated voltage connection and at the tap extremes
6) Temperature rise test at the maximum self-cooled and forced-air-cooled rated kVA load connection
7) Impulse tests on all line terminals
8) Dielectric test consisting of an applied voltage test and an induced voltage test
9) Short-circuit test
10) Seismic tests in accordance with 7.4 (this test may precede the short-circuit test)
11) Repeat of tests 7.3(1) through 7.3(8), inclusive

NOTE — The qualification tests of 7.3 apply to new transformers. For transformers that have been thermally aged or removed from service for qualification purposes, original factory records for 7.3 (1) through 7.3 (8) may be substituted for the tests required before short-circuit and seismic testing. Voltage levels for repeat dielectric and impulse testing, see 7.3(7) and 7.3(8), shall be no less than 65% of original factory test levels (per IEEE C57.12.91-1979 [8]).

7.4 Seismic Qualification Procedure

The methods used for seismic qualification shall be in accordance with IEEE Std 344–1987 [17]. If testing is used for qualification, the following requirements are applicable:

1) The transformer shall withstand a combination of horizontal and vertical OBE and SSE motions producing test response spectra that envelop the respective required response spectra.
2) The number, durations, and direction of earthquake motion tests shall be in accordance with those in IEEE Std 344–1987 [17], or with the specific RRS or generic RRS specified by the user
3) In testing, OBE motion shall precede the SSE motion and shall be in accordance with IEEE Std 344–1987 [17].
4) All interfaces with the transformer shall be representative of specified field conditions. Dummy loads may be used to represent actual field interfaces.
5) During seismic tests, the transformer primary or secondary winding shall be energized at its rated voltage under no load, since dielectric breakdown is the primary failure mechanism.The supply voltage and exciting current shall be monitored continuously during the test.
6) Forced cooling equipment and accessories (if included) shall be operating during seismic tests.

7.5 Pass-Fail Criteria

1) The transformer tested shall meet the criteria of the applicable IEEE standard for qualification tests 7.3(2) through 7.3(8), inclusive, Prior to application of the seismic test. For qualification test 7.3(9), the transformer tested must meet the criteria given in the applicable IEEE Standard.
2) During seismic testing, the inability to withstand rated voltage shall constitute a failure. After seismic testing, the inability to withstand rated voltage or carry rated kVA load shall constitute a failure of the transformer.
3) The inability of forced cooling equipment and accessories (if included) to operate after seismic testing shall constitute a failure of the transformer.

4) Structural changes that occur as a result of the OBE or SSE, but do not impair the ability of the transformer to carry rated kVA load at rated voltage or effect its overall structural integrity, shall be acceptable. Forced cooling equipment must maintain its structural integrity after the seismic test.
5) The transformer tested must meet the criteria of the applicable IEEE Standards for qualification tests 7.3(2), 7.3(3), 7.3(6), 7.3(7), and 7.3(8) after application oft he seismic test.
6) The allowable difference between pre-seismic and post-seismic measurements of the parameters listed in 7.3(4) and 7.3(5) shall not exceed 10% and 7.5%, respectively, unless otherwise specified.

8. Documentation

Documentation required shall be sufficient to show that the transformer meets its specified performance requirements and is capable of surviving normal, abnormal, and design basis events as described in Section 5. It shall be presented in an organized and auditable form.

8.1 Design Qualification

Documentation shall include a tabulation of data from all tests required by 7.3 and the user's specification and shall be in a certified test report. The qualification report shall also include justification that has been agreed upon between supplier and purchaser for omitting thermal aging of the complete transformer and shall document component tests/analysis and conclusions as to qualified life as described in Section 6.

8.2 Seismic Qualification

Documentation shall include results of the tests performed in accordance with IEEE Std 344-1987 [17] and 7.4 in a certified test report, plus any necessary extrapolations.

8.3 Maintenance

Maintenance instructions shall be provided in instruction manuals or in other appropriate documents. The maintenance required to maintain the qualified life of the transformer shall be documented in the qualification report.

Annex A Consideration of the State-of-the-Art of Transformer Insulation Thermal Aging Techniques (Informative)

A1. Application of IEEE Std 323–1983 [16]

IEEE Std 323-1983 [16] describes general methods for the qualification of Class lE equipment of all types for nuclear power generating stations.

This appendix considers the state-of-the-art of transformer technology in relation to thermal aging.

A2. Documents Involved in the Evaluation of Transformer Insulation Materials and Systems

Over a period of many years, there has been much technical activity involved in the evaluation of transformer insulation materials and systems and in the development of transformed loading guides. This has resulted in documents such as the following:

IEEE C57.12.56-1986, IEEE Standard Test Procedure for Thermal Evaluation of Insulation Systems for Ventilated Dry-Type Power and Distribution Transformers (ANSI).

IEEE C57.100-1986 (Reaff 1992), IEEE Standard Test Procedure for Thermal Evaluation of Oil-Immersed Distribution Transformers (ANSI).

IEEE Std 1-1986 (Reaff 1992), IEEE General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation (ANSI).

IEEE Std 98-1984 (Reaff 1992), IEEE Guide for the Preparation of Test Procedures for the Thermal Evaluation of Solid Electrical Insulating Materials (ANSI).

IEEE Std 99-1980 (Reaff 1992), IEEE Guide for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electrical Equipment (ANSI).

IEEE Std 101-1987, IEEE Guide for the Statistical Analysis of Thermal Life Test Data (ANSI).

IEEE Std 259-1974 (Reaff 1980), IEEE Standard Test Procedure for Evaluation of Systems of Insulation for Specialty Transformers.

A2.1 Loading Guides

IEEE loading guides provide guidance for loading at other than rated conditions, including ambient temperatures other than the nameplate rating and in excess of nameplate kVA load with normal life expectancy.

A2.2 Transformer Life Expectancy Example

Fig A1 illustrates relative life expectancy versus hottest-spot temperature curves from IEEE C57.96-1989 [12] for dry-type transformers. Figs A2 and A3 are also from this standard and show actual life expectancy curves to the base 10 and base *e* respectively.

For a transformer constructed with a maximum 220 C hottest-spot insulation system, as defined in IEEE C57.12.01-1989 [4], it is recommended that curve A in Fig A1 be used.

At full nameplate rating with maximum ambient temperature, the hottest spot temperature is 160 °C (50 °C ambient, 80 °C rise, and 30 °C hot-spot gradient). The relative life expectancy is shown to be 55 times normal from Fig A1, which translates into an aging rate of 1/55 or 0.018. If it is assumed that this load condition exists continuously throughout the qualified life for a nuclear plant of 40 years, then the expended life of the transformer is 0.018 40 = 0.72

years. If the normal life expectancy of a transformer is taken as 15 years or it can be obtained from either Fig A2 or A3, then the thermal life remaining in the transformer at the end of qualified life for the plant is $\frac{15 - 0.72}{15} = 0.95$ pu or 95%.

The hottest-spot temperature is a function of the ambient temperature plus the actual load on the transformer relative to its nameplate rating. For transformers that are not continuously loaded to full nameplate rating, the hottest-spot temperature may be determined from equations listed under Section 6 of IEEE C57.96-1989 [12]. This calculated temperature should be utilized in lieu of the value used in the above example.

- Although the 220 °C thermal aging curve was originally developed for insulation systems in sealed transformers, this same curve is applicable to the same insulation systems that are now used in ventilated-type transformers (see IEEE C57.96-1989 [12]).

For transformers with other insulation systems, data obtained from 6.2 may be used to develop an insulation life relationship to describe the particular insulation system versus operating hottest-spot winding temperature. This relationship, in combination with temperature ratings, load conditions, and ambient temperature, may be used to obtain similar results.

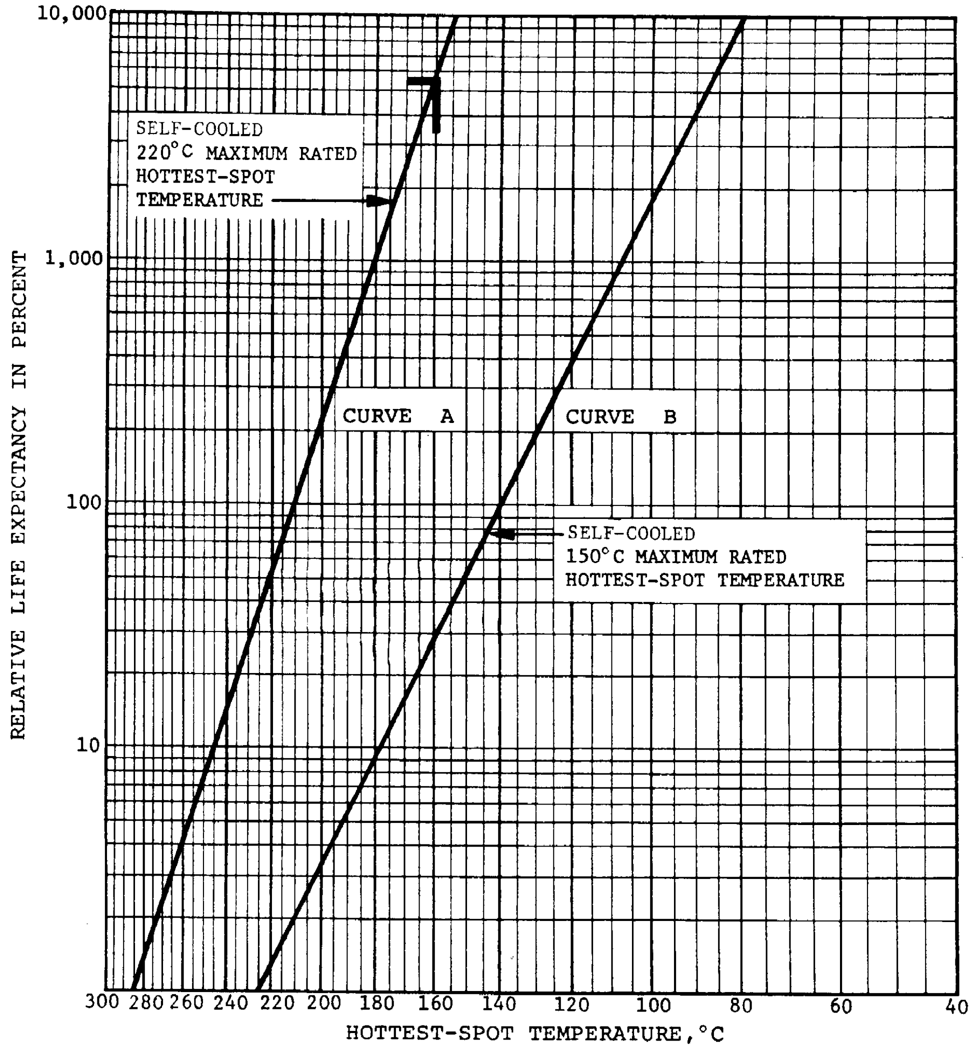

Figure A1—Life Expectancy Versus Hottest-Spot Temperature

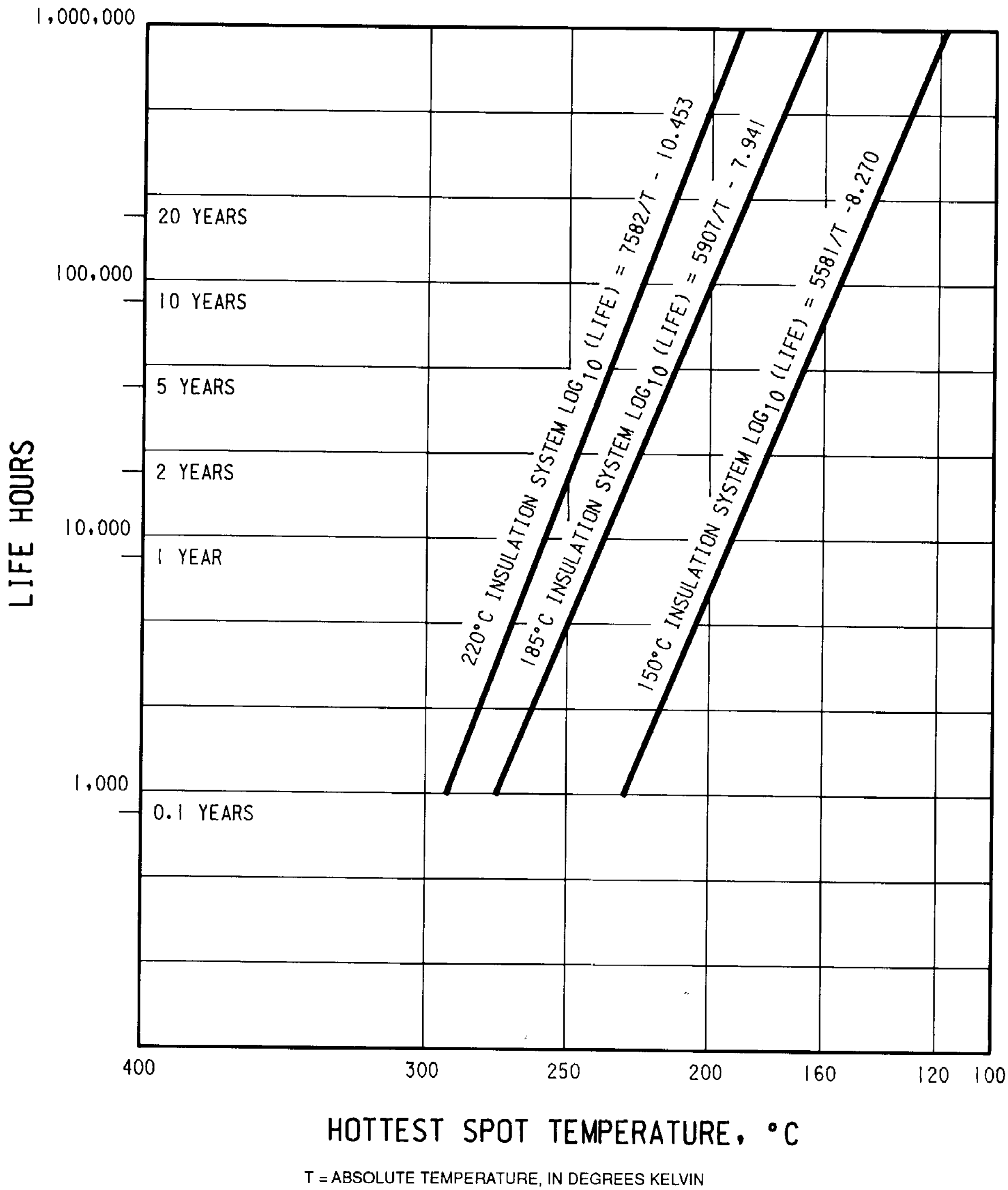

Figure A2—Life Expectancy Curve — Base 10

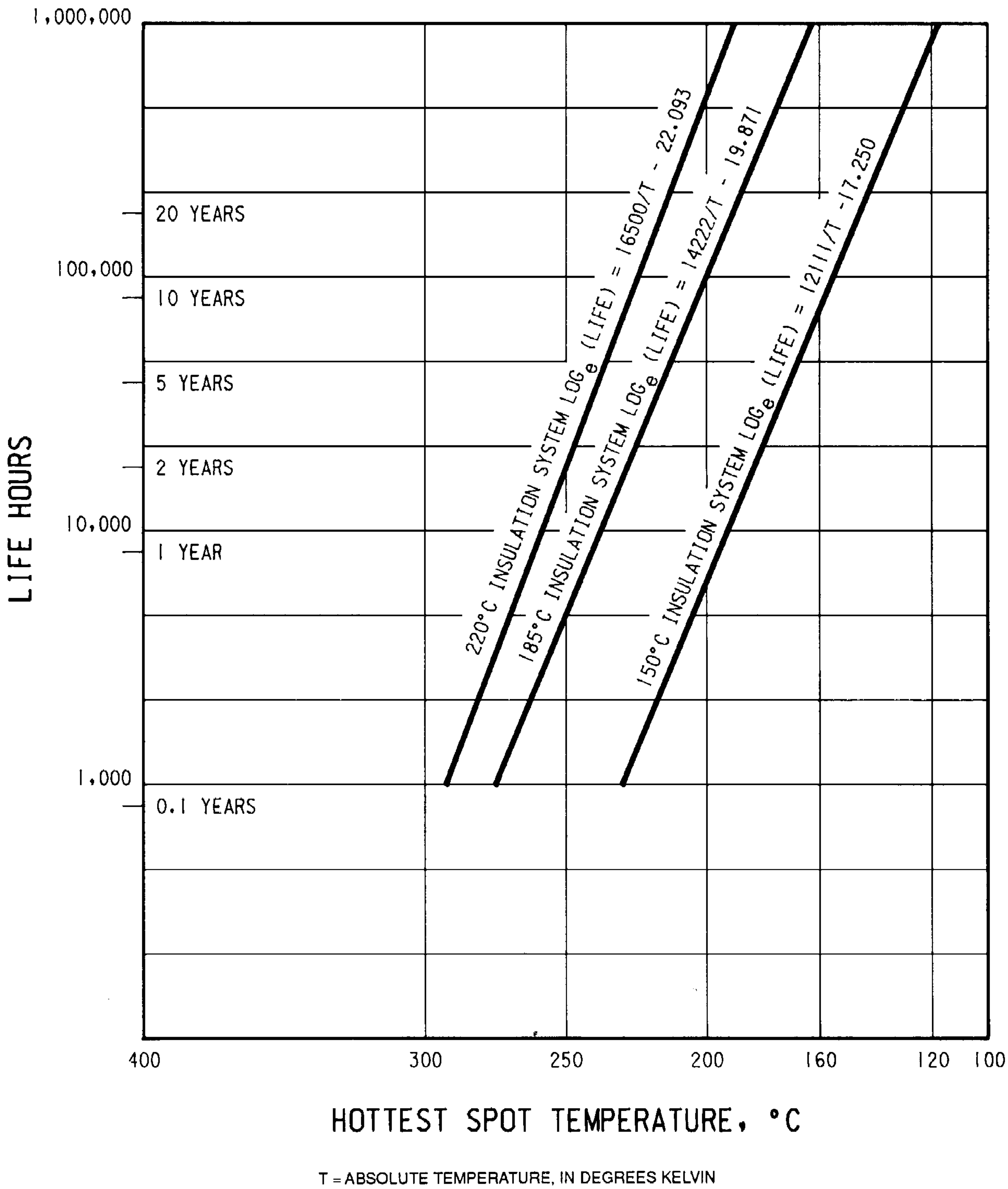

Figure A3—Life Expectancy Curve — Base *e*

A3. Characteristics Typically Involved in Documents Pertaining to the Thermal Aging Evaluation of Electrical Insulation Materials or Systems

Review of the documents listed in Section A2 reveals various items common to most of these procedures when purposes and techniques are examined and compared.

A3.1 Test Specimen

Aging tests are most commonly conducted on individual insulation materials or models representative of actual insulation systems. Care should be taken, when using data on single materials, that any chemical reactions between this material and any other materials do not void the system evaluation. Insulation system tests are usually conducted with nonfunctional representative transformer models. Tests on insulation systems for certain specialty and distribution-type transformers usually employ full-size, functional transformers.

A3.2 Number of Test Specimens

A number of specimens are commonly tested; a minimum of three is recommended. The accuracy and reliability of the results are considered to improve as the number of test specimens is increased.

A3.3 Actual Duration of Tests

Actual test duration times at the elevated test temperatures are chosen so that there will be approximately the same number of aging cycles to failure at each of the different aging temperatures. The elevated aging temperatures and times are also chosen to allow obtaining meaningful data in a reasonably short period of time (more than 100 h).

A3.4 Extrapolation of Test Data

Extrapolation is commonly used to estimate the probable endurance of insulation materials and/or systems under the specified conditions.

A3.4.1 Time Extrapolation

Time extrapolation is commonly performed using an insulation life equation adapted from Arrhenius rate constants. This equation is based on chemical rate reaction theory and indicates that if the logarithm of life (time) is plotted as the ordinate of a graph versus the reciprocal of the absolute temperature as abscissa, a linear relationship will result. This relationship is expressed mathematically as

$$\ln L = A + B/T$$

where

L	is life, in hours
T	is absolute insulation temperature, in degrees Kelvin
A and B	are constants for each material or insulation system

A3.4.2 Insulation Life Relationship

The insulation life relationship is particularly useful in providing acceleration in the testing, evaluation, and relative comparisons of insulation systems. By aging at three or more temperatures, each separated by 10 °C or more, greater than the maximum anticipated service temperature and plotting the results as described, the plotted failure points usually approximate a straight line, which can be extrapolated and compared to identically obtained results for a known service proven insulation system to estimate the expected life of the item involved at some lower temperature. The insulation life relationship permits determination of qualified life using a calculation based upon explicit data with a high level of confidence in the 5–20 year range. In establishing a longer qualified life, extrapolation techniques are commonly used based upon the same explicit data. This application of the insulation life relationship results in a decreased confidence level proportional to the length of the extrapolation. Therefore, qualified life values in the 20–40 year range may be inherently less precise than the shorter range values.